NDTCE'09, Non-Destructive Testing in Civil Engineering
Nantes, France, June 30th – July 3rd, 2009

Damage assessment in post-tensioned concrete viaduct by *b*- and *Ib*-value analysis of AE signal

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Abstract

Acoustic emission (AE) technique is gaining increasing interest for application in civil engineering. AE indeed is a passive non intrusive technique that can be applicable either in Structural Health Monitoring - SHM - (global evaluation) and in defect localization (local evaluation). However a great effort yet have to be done on data handling and data interpretation, especially in eliminating acoustic noise generated, for example, by not structurally significant concrete micro-cracking under loading condition.

Some interesting results in AE analysis can be obtained by applying relationships already applied in earthquake seismology and in rock fracture studies. Aim of the present work was to assess the capability of the *b*- and I*b*-value analysis, to evaluate damage condition of concrete structures. AE monitoring was used during proof loading of two seriously damaged viaduct. The analysis of the temporal variation of *b* value as well as the analysis of the acoustic quiescence was also performed with promising results.

Résumé

La technique de l'émission acoustique (AE) est de plus en plus intéressante pour l'application en génie civil. L'AE est en effet une technique passive et non intrusive qui peut être appliquée soit en surveillance de la santé des structures - SHM - (évaluation globale) soit pour la localisation des défauts (évaluation locale). Toutefois, un grand effort est encore à fournir sur le traitement et l'interprétation des données, en particulier dans l'élimination du bruit acoustique généré, par exemple, celui émis par les micro-fissurations qui ne sont pas structurellement importantes sous condition de chargement. Des résultats intéressants en analyse de l'AE peuvent être obtenus par l'application de relations déjà utilisées en sismologie, dans l'étude de tremblement de terre et dans les études des fractures de la roche. L'objectif de ce travail est d'évaluer la capacité de l'analyse des valeurs *b* et I*b*, afin d'évaluer les désordres des structures en béton. L'AE suivi a été utilisé au cours des essais de chargement des deux viaducs gravement endommagés. En outre l'analyse de la variation temporelle de la valeur *b*, ainsi que l'analyse de l' inactivité acoustique a également été effectuée avec des résultats prometteurs.

Keywords

Acoustic Emission, data analysis, proof loading, corrosion, post-tensioned concrete.

1 Introduction

Segmental cast-in-place post-tensioned structures were extensively used in Italy during the reconstruction processes soon after the Second World War, as innovative design solutions adopted for a rapid and economical building of bridges. After 50 years, most of those structures have formally concluded their design service life, but social and economic reasons frequently force their owners toward rehabilitative solutions instead of undertaking demolition and rebuilding. The rehabilitation project and the evaluation of the residual load-carrying capacity involves the solution of unusual problems arising during the degradation assessment step linked to the peculiar geometry and to the structural weakness of such constructions. For such structures, the main concern is the status of prestressing or post-tensioning cables.

AE seems to be very promising as structural health monitoring technique since it is not invasive, allows a volume evaluation and at the same time has the possibility to locate discrete defects. AE was however introduced very recently in the field of civil engineering, nevertheless several health indexes based on the analysis of AE parameters have been proposed and applied in SHM as well as "Load ratio", "Calm ratio", "Felicity ratio" and "Historical index" [1-2] or " Relaxation ratio" [3]. AE analysis could be significantly improved by adopting some procedure already used in the field of geophysics and earth science. Among various parameters, the most significant one is the *b*-value which is derived from the amplitude distribution data of AE following the methods used in seismology [4]. The *b*-value is defined as the 'log-linear slope of the frequency–magnitude distribution' of AE. It represents the 'scaling of magnitude distribution' of AE, and is a measure of the relative numbers of small and large AE which are fingerprints of cracks occurring in materials under stress. While testing the materials undergoing brittle failure, the *b*-value is found to range from 1.5 to 2.5 in the initial stages [5]. It then decreases with increase in stress to attain values ≈ 1.00 and less, showing temporal fluctuations as the impending failure approaches in the material. A high *b*-value arises due to a large number of small AE hits (or events) representing new crack formation and slow crack growth, whereas a low b-value indicates faster or unstable crack growth accompanied by relatively high amplitude AE in large numbers [5-6]. Aim of this work was to asses if the application of *b*, I*b* values and other related analysis could be successful applied in evaluating damage degree in post-tensioned concrete structures under loading.

2 b value and Ib value analysis

Starting from the original Gutenber-Richter formula the *b* value was calculated as the slope of the function

$$LogN=a -b(A_{dB}//20) \tag{1}$$

where N is the number of AE events with an amplitude higher than A_{dB}. The *b*-value analysis of AE is in general applied to groups of subsequent events, a group of 100 events was used in this work. In order to avoid the problem to define amplitude range and the number of AE data to obtain the *b*-value the improved *b*-value analysis (I*b* value) was proposed by Shiotani [7]. The I*b*-value is defined by utilizing some statistical values of the amplitude distribution as mean and standard deviation and obtained from

$$Ib=\frac{\log_{10} N(w_1)-\log_{10} N(w_2)}{(\alpha_1+\alpha_2)\sigma} \tag{2}$$

where $N(w_1)$ is the accumulated number of AE events in which the amplitude is more than μ-$\alpha_1\sigma$ and $N(w_2)$ is the accumulated number of AE events in which the amplitude is more than $\mu+\alpha_2\sigma$, σ is the standard deviation of the magnitude distribution of one group of events, μ is the mean value of the magnitude distribution of the same group of events, and α_1 as well as

α_2 are constants. To calculate such constants the procedure summarized in [8] has been followed in this work.

2.1 Temporal variation of b-value

The hypothesis that the *b*-value decreases prior to the occurrence of an earthquake is not new. Fielder [9] and Smith [10], among others, have shown that in some cases significant changes in *b*-value precede large earthquakes. Scholz [11], after testing various rock types, suggested that the *b*-value is inversely related to the accumulation of stress in a given region. With high-quality data sets from the Parkfield segment of the San Andreas Fault, Wiemer and Wyss [12] found evidence that supports the inverse dependence of *b* on stress for crustal earthquakes. From these and other similar studies, one might speculate that in concrete structures a decreasing *b*-value could be indicative of increasing stress levels, i.e. indicative of an impending fracture.

2.2 Acoustic quiescence - Z value

As reported above it results that changes in seismic activity patterns can occur during the process of preparation of large earthquakes, and such changes possibly are the most reliable long-term earthquake precursor examined to date. This consideration could be transferred to cracking phenomena in concrete structure. A parameter to describe changes in seismic activity is the seismic quiescence. Seismic quiescence is a decrease of the mean seismicity rate as compared to the background rate in the same crustal volume judged as significant by some clearly defined standard. One commonly used test for comparing seismicity rate changes is the *Z*-value test for a difference between two means. The *Z*–value measures the significance of the difference between the mean seismicity rates μ_1 and μ_2 within two time interval. Where σ and n are, respectively, the standard deviation of the rate and number of samples in the group.

$$Z=\frac{\mu_1-\mu_2}{\sqrt{\frac{\sigma_1^2}{n_1}+\frac{\sigma_2^2}{n_2}}} \tag{3}$$

The *Z*-value is an indication of the strength of a change, where the amount of change of a variable as well as the corresponding standard deviations and also durations of the periods used to define the change are considered. Negative *Z*-values indicate rate increases while a positive *Z* corresponds to rate decrease. Magnitude signature plots are used to evidence seismicity rate changes that are often a strong function of magnitude. To determine the time of a single seismicity rate change, the *Z* test can be applied repeatedly to the data constructing a function, *LTA(t)* (Long term average) [13]. *LTA(t)* is the *Z*-value resulting from the comparison of the rate within a window, μ_{Win} and the background rate, μ_{All}, here defined as the overall mean rate in the volume. It was found that all these events show a similar pattern. A significantly high *Z*-value is found at the beginning of a quiescent period preceding the earthquake.

3 Experimental

The Agrò and Fiumedinisi viaducts, on the national road number 114 on the eastern coast of the Sicily Island were designed in 1954 by Riccardo Morandi and built during 1955-56. They are 13- and 8-spans viaducts, respectively, with a span length of ~22 m. The viaducts

were built by using segmental cast-in-place post-tensioned prestressed concrete box girder, each span was characterized by a five-cell longitudinal trapezoidal void section box girder. Four cast-in-place diaphragms were provided at each end and along each span of the bridge. An 11-cm-thick top concrete slab was monolithically cast-in-place. Post-tensioning internal tendons consisted of 5-mm wires bundle placed in 40-mm diameter ducts obtained in the box girder walls. Following detailed visual and instrumental inspection, which showed a critical degradation status due to seaside vicinity and to the "advanced" age, it was decided to evaluate damage effects on structural behavior by means of proof-loading test and a simultaneous AE monitoring.
The set-up of the AE system involved a long series of calibration tests on concrete samples at rest, and by carrying out breaking of pencil-leads of different hardness and dimensions on the surface of samples; these tests have been carried out in different environments to test the effectiveness of filter system and to calibrate the "trigger threshold" suitable to extract the significant components of AE signals. AE signals were recorded by a ten-channel Vallen AMSYS-5 measurement system. The piezoelectric transducers for concrete were Vallen VS30-V with a flat response between 23-80 kHz. Threshold values after calibration were set at 35 dB, a total of ten sensors were used and positioned on the lateral side of different segments of box girders for each measurement (Fig. 1).
Proof loading test consisted of two loading cycles. I° loading cycle: the load was produced by a 30 tons (0.3 MN) truck set in the middle of the span and a subsequent 20 tons (0.2 MN) truck set on the parallel lane, trucks were then allowed to move off. II° loading cycle: the load was produced by two 30 tons trucks set on the same lane, then by a 20 tons truck set on the parallel lane and a subsequent 30 tons (0.3 MN) truck set on the same lane, trucks were then allowed to move off. For each load test step, it has been possible to evaluate the displacements in the middle of the span in the border and in the center.


Figure 1.*Sensor location on the beams*

4 Results and discussion

For space reaseon only the analysis carried out on AE hits collected from a single channel (channel 10 on Agrò viaduct and channel 5 on Fiumedinisi viaduct) will be reported, but similar results were obtained from the other channels. As reported in literature change in *b* values could be related to different cracking mechanism occurring in concrete. During the first loading cycle (Fig. 2), higher *b*-values were expected to be correlated with the opening of micro-cracks. *b*-values, showed a mean decrease as the load increased. The second loading cycle was characterized by a large scatter of *b*-values. Especially for channel 10 the I*b* value resulted more sensitive in indicating changes in AE activity related to micro-cracks and cracks opening. The increase in I*b* value during the unloading step could be related to shear cracks mechanism and surface crack sliding occurring during crack closure. Magnitude plot evidenced the difference in acoustic emission of the two viaducts differentiating in damage density. Plots were obtained by comparison of the AE activity during the two loading cycles. The increase in the high negative *Z* values of channel 10 indicate a higher rate of high magnitude AE hits.

The Long term average function (*LTA(t)*) allowed to identify for the same viaduct (by the deep minima in the curve) the second loading cycle as the most severe one, i.e. with the occurrence of most severe cracking phenomena (Fig.3). Even if further studies on the application of this type of AE data analysis are required, the results up to now gained seem very promising in the hypothesis to adopt such procedure for a SHM.

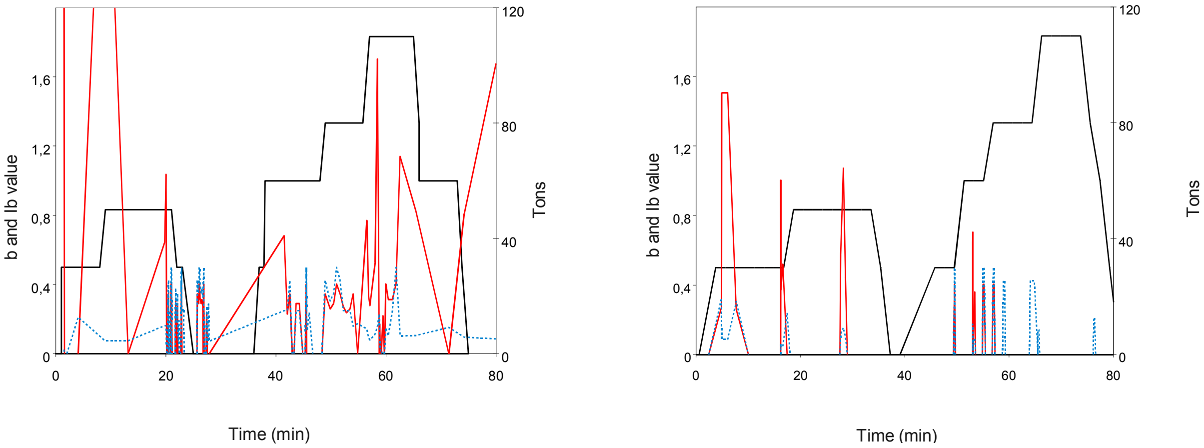

Figure 1. *b and Ib values vs time. b value, red continuous line; Ib value, blue dashed line; load, black continuous line. Channel 10, highly damaged beam, Agrò viaduct (left side), channel 5, low damaged beam, Fiumedinisi viaduct (right side).*

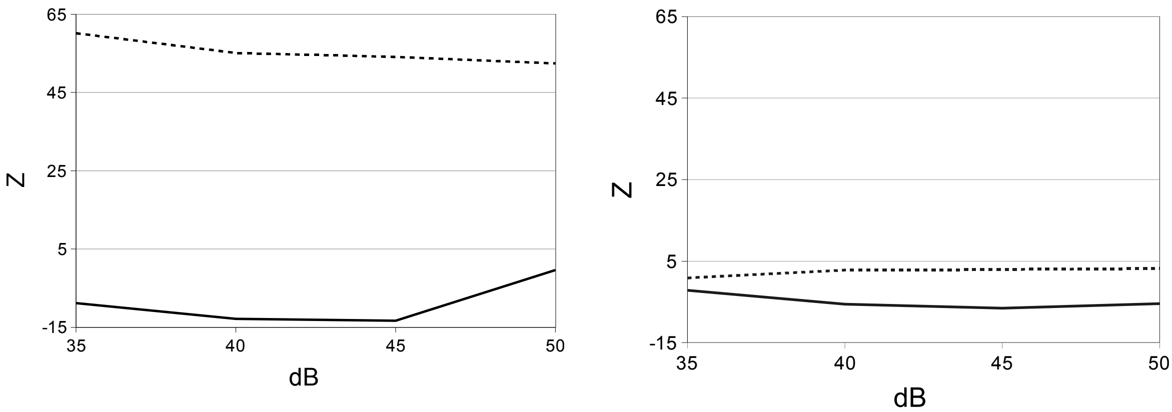

Figure 2. *Magnitude signature plot (distribution of AE rate changes in the magnitude domain) between the first loading cycle and the second loading cycle. Magnitude band and above, continuous line; Magnitude band and below, dashed line. Channel 10, highly damaged beam, Agrò viaduct (left side), channel 5, low damaged beam, Fiumedinisi viaduct (right side).*

5 Conclusions

The analysis of AE data from cracking concrete element could be significantly improved by adopting some procedure already used in the field of geophysics and earth science. Among various parameters, the most significant one is the *b*-value. The *b*-value and especially the I*b*-value analysis have furthermore the advantages that only a limited number of sensors are required and that only two input parameters (energy of the signal, event number) are needed. The analysis of the rate of change in acoustic activity seems to be very powerful in predicting incipient fracture under loading condition. These techniques have been successful applied in evaluating the different damage degree in post-tensioned concrete structures under loading.

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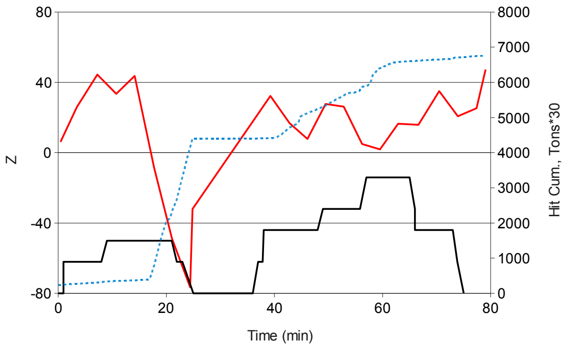

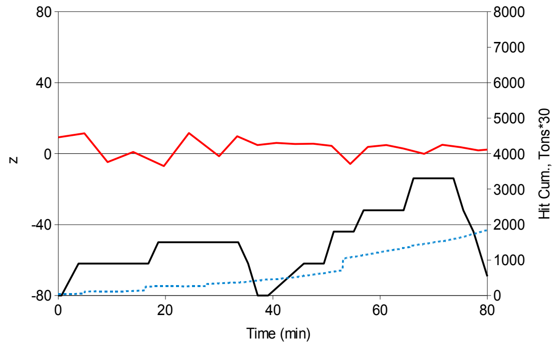

Figure 3. *LTA(t) functions. Z-value, red continuous line; Cumulative hits, blue dashed line; Load, black line. Channel 10, highly damaged beam, Agrò viaduct (left side), channel 5, low damaged beam, Fiumedinisi viaduct (right side).*

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